FINAL REPORT
ON
STUDY OF SUBMINIATURE TOTAL TEMPERATURE PROBES

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Prepared by:

R. E. Larson
A. R. Hanson

Submitted by: Roy E. Larson
R. E. Larson, Manager
Heat Transfer and
Fluid Mechanics

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Approved by: A. A. Anderson for
S. P. Jones
Vice President, Research

APPLIED SCIENCE DIVISION
Litton Systems, Inc.
2003 East Hennepin Avenue
Minneapolis, Minnesota 55413

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ABSTRACT

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This is the final report of research on subminiature total-temperature probes. It summarizes the development and fabrication of several types of small total-temperature probes, and presents calibration results obtained for these probes in the wind-tunnel probe-calibration facilities.

The objective of the study was to develop subminiature total-temperature probes which could be utilized in various boundary-layer studies, to be carried out in test facilities at the George C. Marshall Space Flight Center. The attainment of small size and the development of the special fabrication techniques required for these small probes were considered more important than satisfying an absolute accuracy requirement.

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FINAL REPORT ON STUDY OF SUBMINIATURE TOTAL TEMPERATURE PROBES

I. INTRODUCTION

The general objective of this study was to develop subminiature total-temperature probes, which could be utilized in various boundary-layer studies now being carried out in test facilities at the George C. Marshall Space Flight Center. Probes of the required size (of the order of 1/32 inch O. D. or smaller) are not presently available commercially, so new fabrication techniques had to be developed.

The attainment of high temperature-recovery factors, over a range of freestream conditions, requires close control of the internal flow characteristics of the probe. The sensing element must be carefully designed to minimize conduction errors, and efficient radiation shielding is required to reduce radiant heat losses. In general, these necessary design features are not compatible with small size, so simultaneous optimization of these conflicting requirements was required.

There exists a large body of literature related to total-temperature measuring probes. References 1 through 10 well represent the "state-of-the-art", and References 3, 9 and 10 were especially pertinent to the present study. What emerges from the literature as of particular significance is that the optimization of probe performance requires careful design, and becomes increasingly difficult as the probe size is decreased.

This program was a cooperative effort between the Litton Applied Science Division (ASD) and the University of Minnesota Aero-Hypersonic Laboratory (AHL). The high-pressure probe calibration tests were performed in the ASD free-jet wind tunnel, while the low-pressure tests were performed in the AHL facility, which discharged into a vacuum chamber.

All probe configurations tested had a single radiation shield, and the sizes varied from 0.028 to 0.013 inch O.D. Both beaded and lap-welded thermocouple-junction configurations were utilized, with wire diameters from 0.0005 to 0.0015 inch. Shown in Figure 1 are schematic drawings of the three major probe configurations tested.

The present studies indicate that it is possible to build a very small total-temperature probe, having a good recovery factor. However, fabrication procedures must be carefully controlled, as small deviations from the desired configuration result in considerable variations in the probe performance. A negative, though predictable finding, is that these small probes are extremely sensitive to dirt particles entrained in the flow. Rapid degradation of the probe performance characteristics results when the thermocouple sensing element is sandblasted too severely or is forced into contact with the probe case. The initial probe design was based on the present "state-of-the-art", but modified and improved versions evolved from analysis of the early test data.

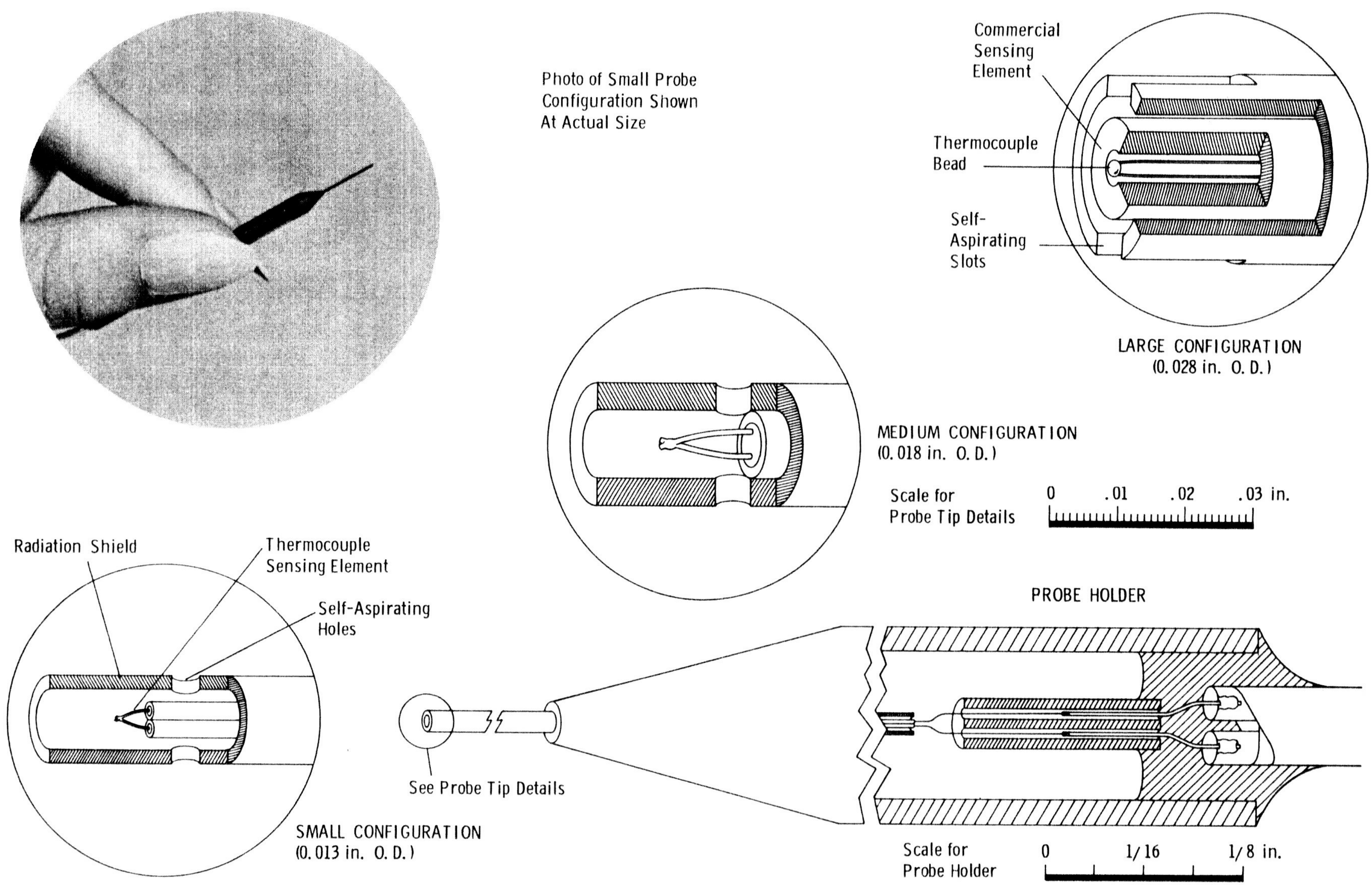

Figure 1. Subminiature Total Temperature Probe Configurations

II. EXPERIMENTAL EQUIPMENT AND TECHNIQUES

A. Probe Calibration Facilities

1. Test Facility at the University of Minnesota

The probe calibration channel is connected to the pressure and vacuum components of the large wind tunnel system. This facility consists of a storage-type heater and a small enclosed free-jet wind tunnel, mounted within a gas-fired furnace. Figure 2 is a photograph showing an overall view of the facility and associated components. Stainless steel one-inch exit-diameter nozzles, at Mach 1, 3 and 5, were utilized for these measurements. The miniature total temperature probes were mounted at the nozzle exit. The test-section components are shown in Figure 3, and Figure 4 is a photograph of a probe installed in the test section. All parts were made of stainless steel, and the components were assembled with high-temperature silver solder. Because of the small nozzle size, near continuous operation is possible over a wide range of stagnation temperatures and pressures.

This tunnel has a maximum stagnation pressure capability of 600 psig, and can produce stagnation temperatures as high as 1200°F. Coarse control of the stagnation pressure is provided by a 6-inch butterfly valve, and fine control by a smaller valve connected in parallel. The exit of the tunnel is connected to the vacuum system, with control of the nozzle exit pressure provided by a gate valve.

Figure 5 is a photograph of the storage heater, comprised of four pipes mounted inside the furnace, which are filled with 1/4-inch-diameter spheres of a pure grade of aluminum oxide.

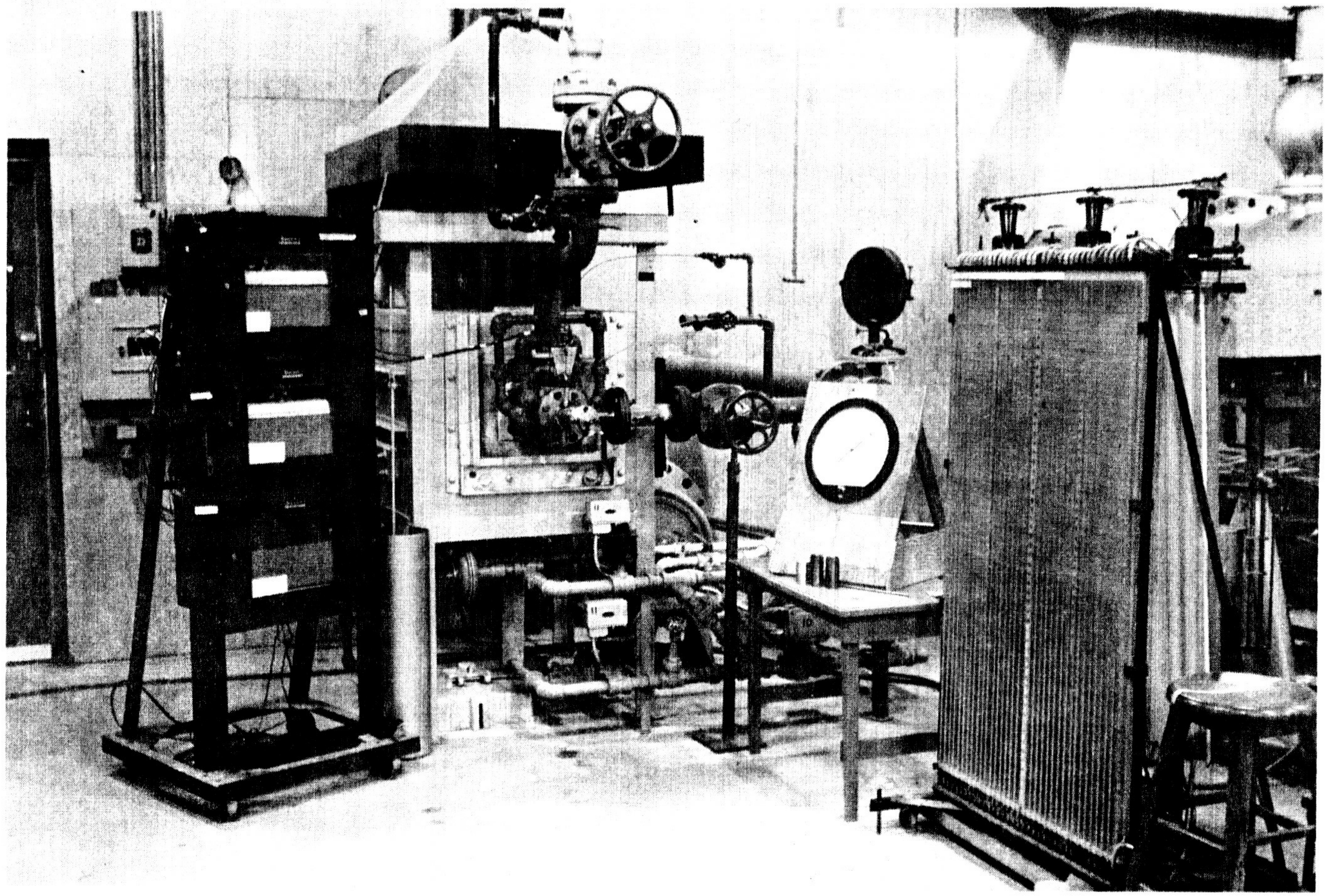

Figure 2. Aero Hypersonic Laboratory Temperature Probe Test Facility and Associated Instrumentation

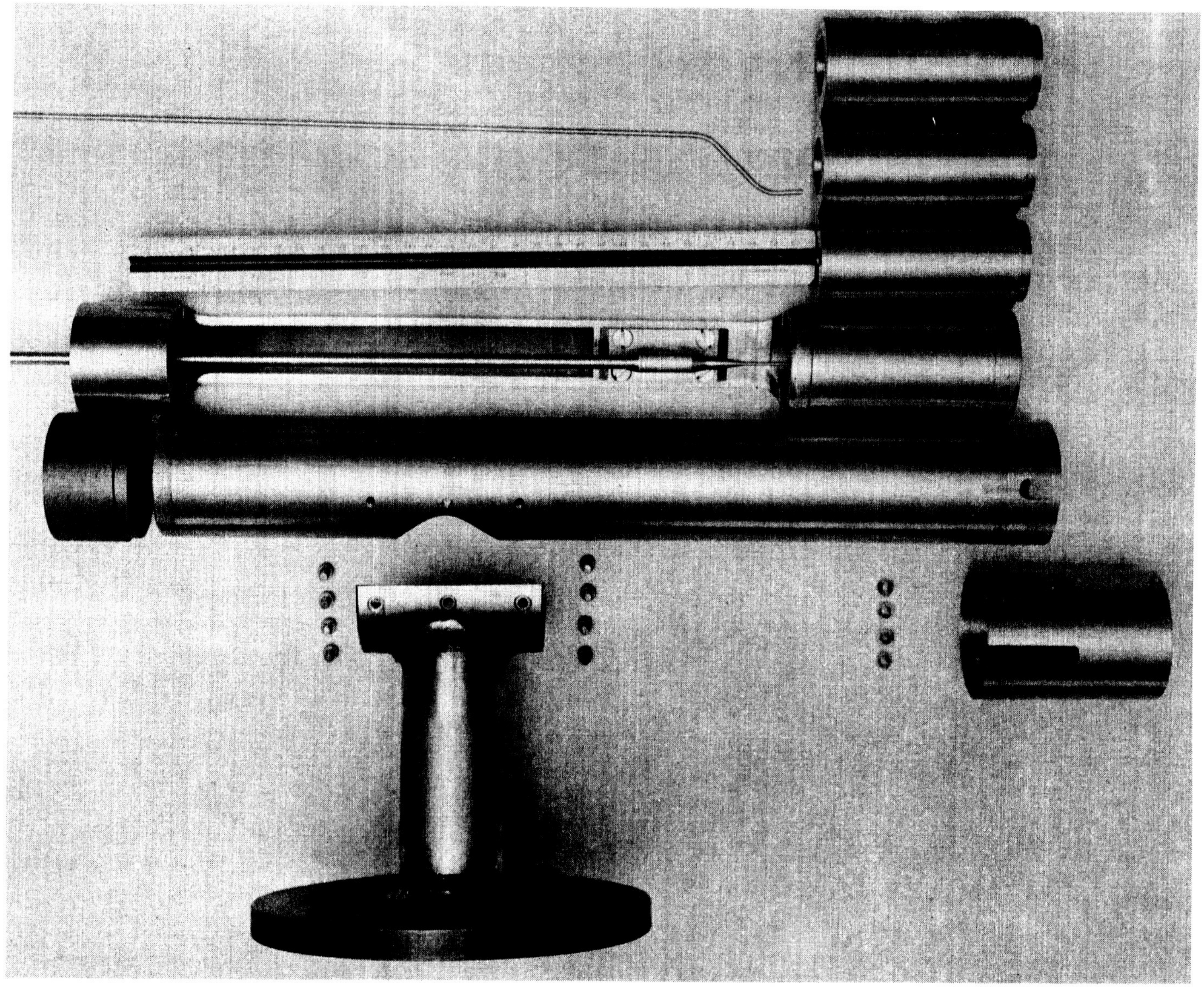

Figure 3. Wind Tunnel Test Section Components

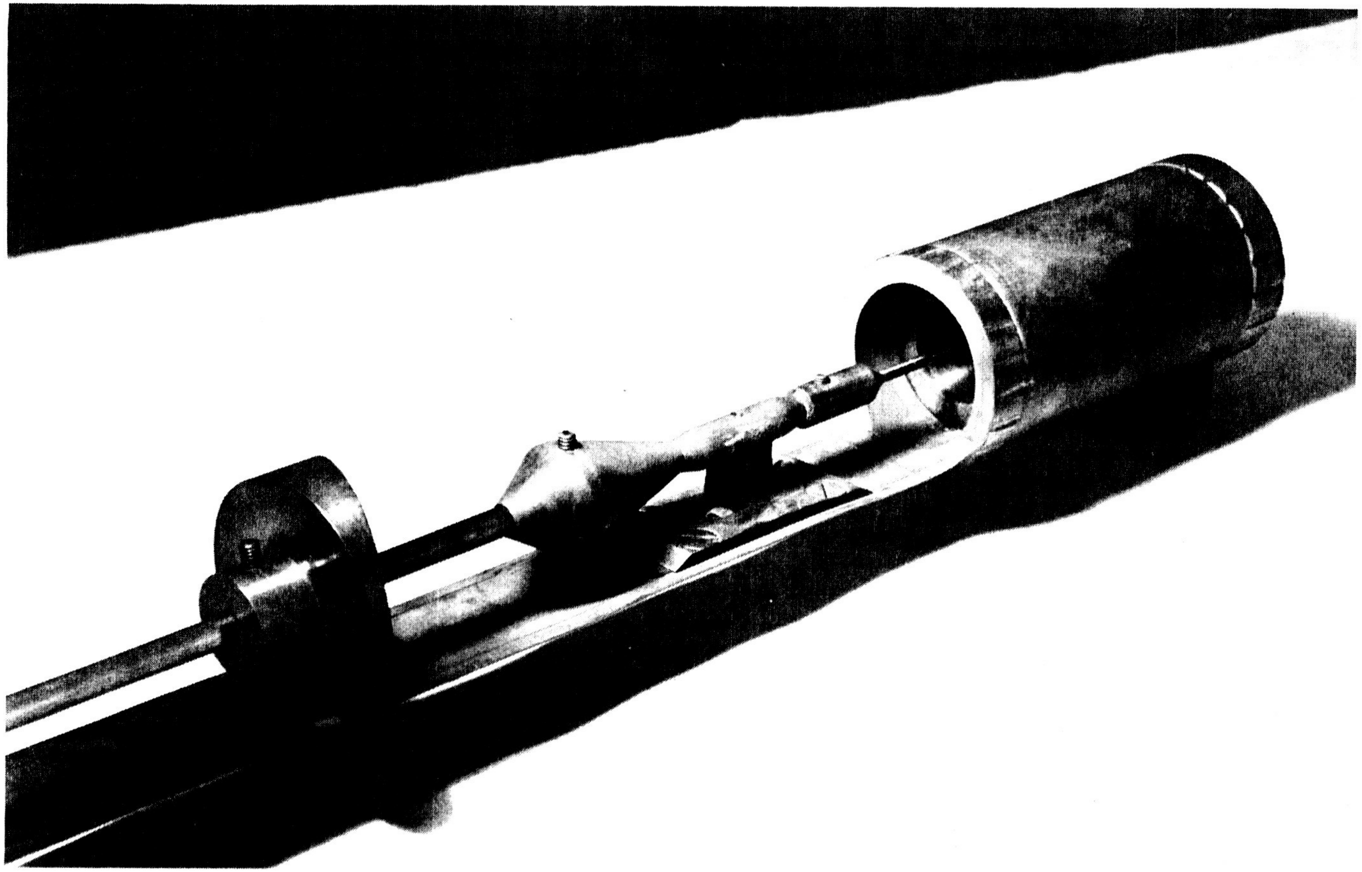

Figure 4. Temperature Probe Installed in Test Section

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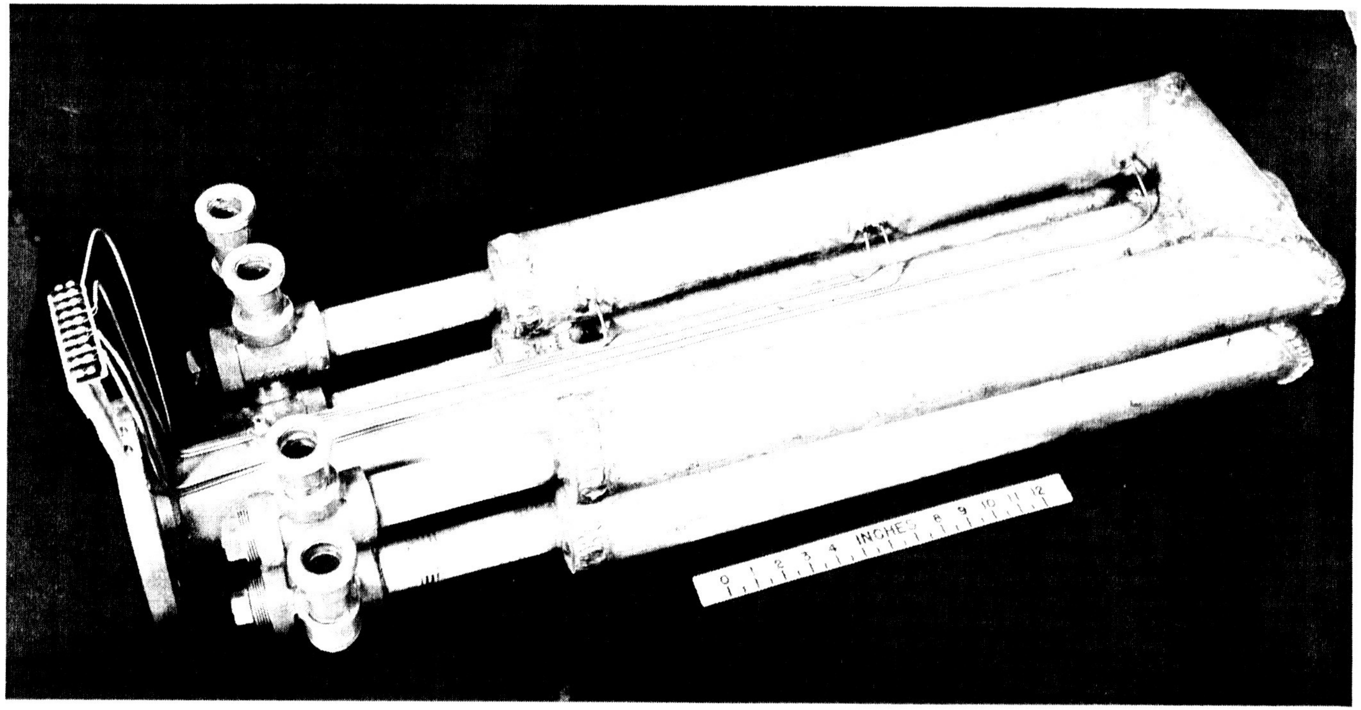


Figure 5. Storage Heater Assembly

As these small thermocouple probes are extremely sensitive to dirt particles entrained in the flow, a special filter assembly was designed and fabricated for use with this facility. The filter assembly consists of Poroloy stainless steel woven mesh, which has an effective pore size of 5 to 10 microns. Following the filter are flow-straightening and turbulence-damping components which consist of five units of variable porosity. The first three units of this assembly are made of various porosity stainless steel plates, and the last two units are made of wire mesh material, as shown in Figure 6. A view of the wind tunnel assembly is shown in Figure 7.

The reference stagnation temperature was measured with a forced-aspirated chromel-alumel probe mounted upstream of the nozzle. The thermocouple junction was made of lap-welded 0.002-inch thermocouple wire which provided a rapid response to changing temperatures.

A Mach number calibration was performed for the nozzles, over the temperature and pressure range required for the probe calibration tests. Several difficulties were encountered in this phase of the work. During the initial cold runs, fluctuations were observed in the stagnation pressure readings. At first it was thought that these were caused by the "blind" end of the tunnel acting as a resonant tube, a conjecture which appeared to confirm the heating of the tunnel end wall. However, blanking off of this region did not solve the problem. Closer examination revealed that the fluctuations were occurring in the stagnation chamber. The problem was then eliminated by the installation of the series of variable-porosity, stainless steel plates described earlier.

After these various difficulties had been overcome, the nozzles were calibrated. These data are shown in Figure 8 for the Mach number 3 and 5 nozzles. It will be noted that the effect of tunnel

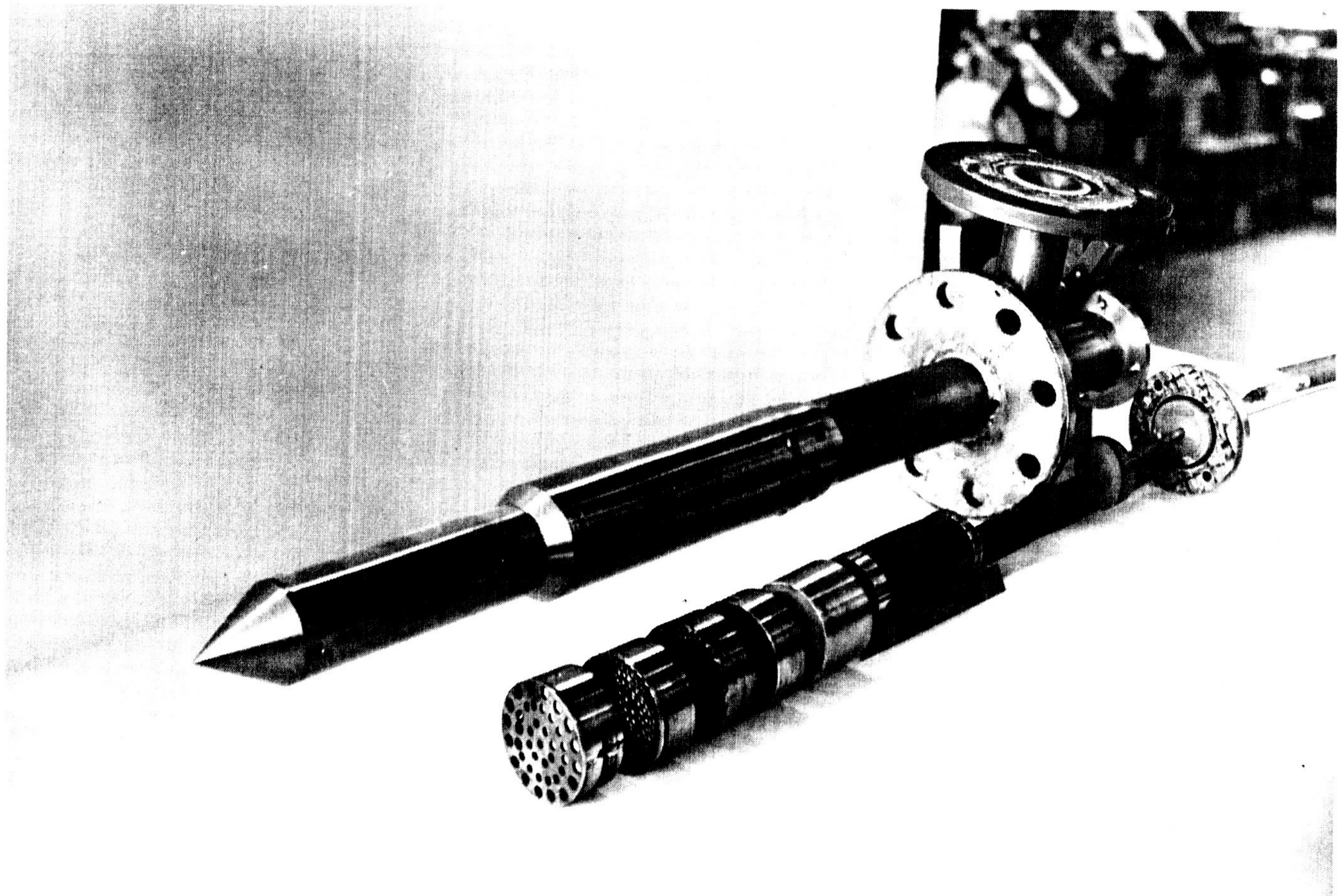


Figure 6. Filter Assembly and Flow Straightening Components

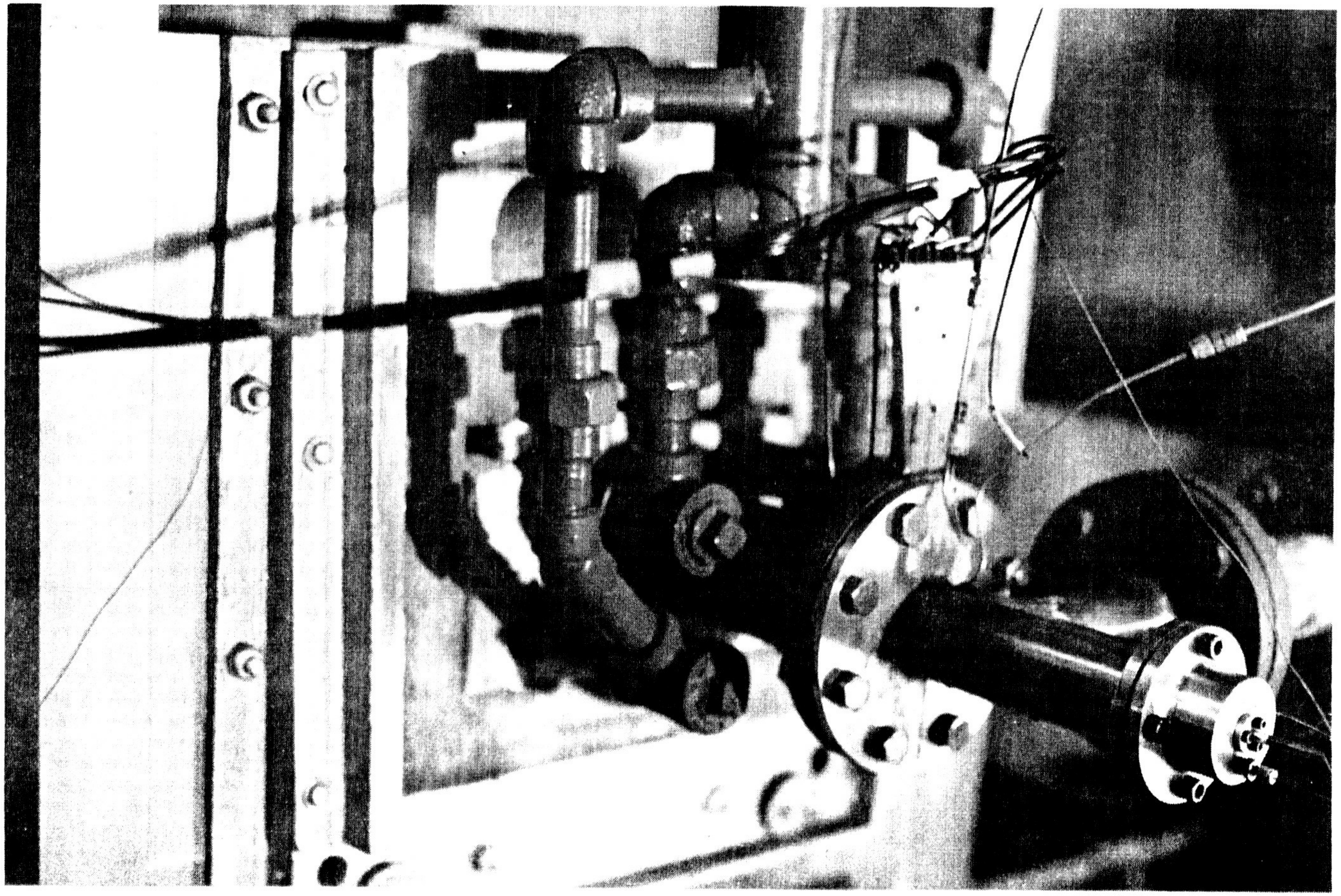


Figure 7. Wind Tunnel Assembly

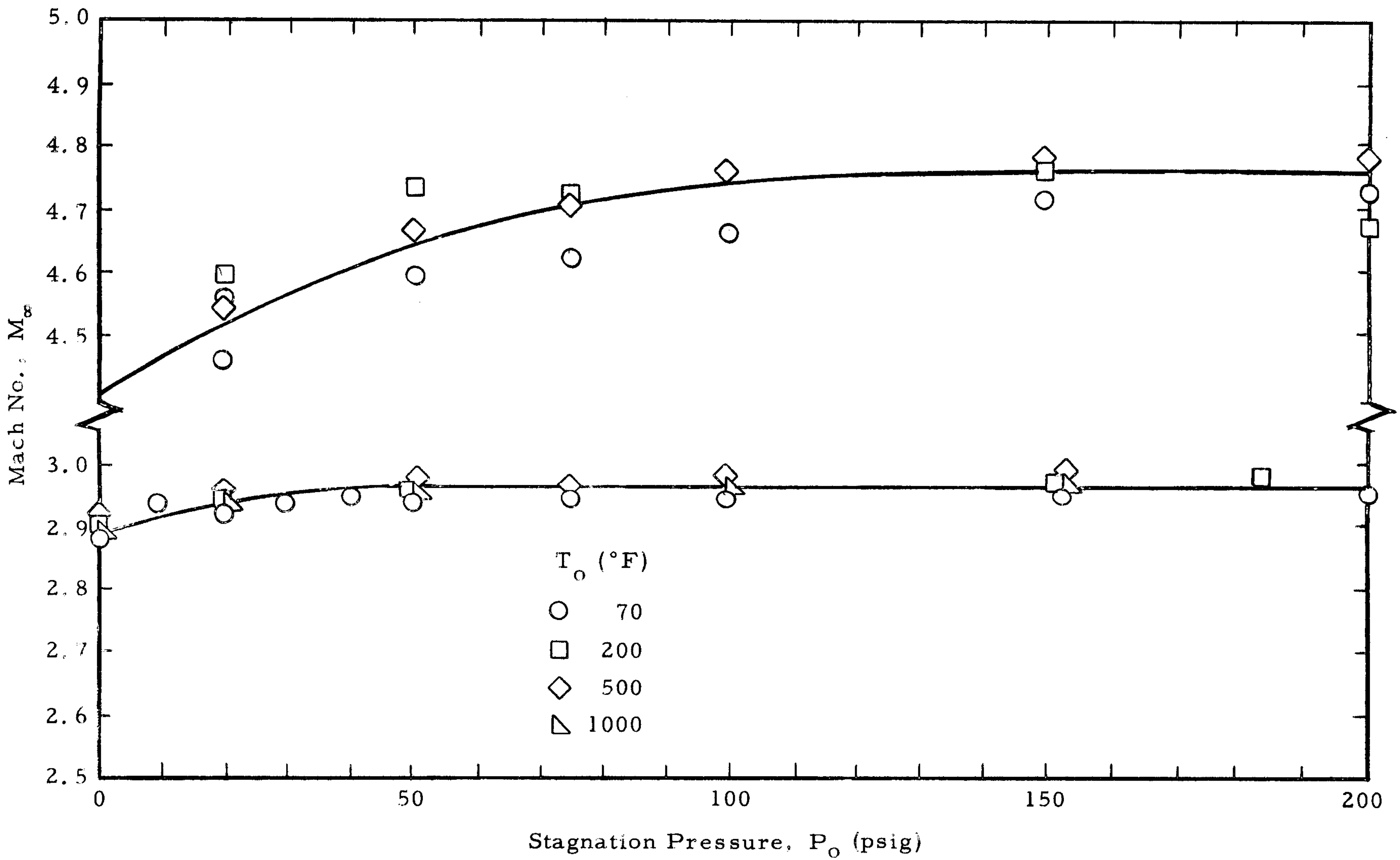


Figure 8. Nozzle Calibration Curves

stagnation temperature is reduced as the stagnation pressure is increased. In addition, it can be seen that the influence of temperature is quite small.

2. Test Facility At Litton

In the AHL calibration facility, the wind tunnel test section and filter assembly are located within the heater. After a certain amount of "soaking" during the heating period, the temperature of the tunnel walls rises considerably above ambient temperature. This is an effect which tends to reduce the radiative heat loss from the probe. For this reason, it was decided to carry out some tests in the ASD wind tunnel facility which has a free-jet nozzle exhausting to the atmosphere.

This high-temperature, high-pressure wind tunnel facility has a free-jet configuration with a nozzle exit diameter of 1 inch. Stainless steel conical nozzles, producing Mach numbers of 1.5, 2.0, 2.5, 3.0 and 3.5, are included with this facility, as shown in Figure 9. It is designed to operate at stagnation temperatures to 1500°F at a stagnation pressure of 1500 psig. During operation, air flows from the tanks through a manual control valve, and into the cylindrical heat exchanger where it is heated to the stagnation temperature desired. The gas is then expanded through the supersonic nozzle into the test section. The wind tunnel stagnation pressure and stagnation temperature are measured in a stilling chamber upstream of the supersonic nozzle. The tunnel operator reads the stagnation pressure, while controlling the airflow rate to the system, and the temperature is recorded on instruments shown in Figure 10. A filter assembly similar to that in the AHL tunnel is shown in Figure 11.

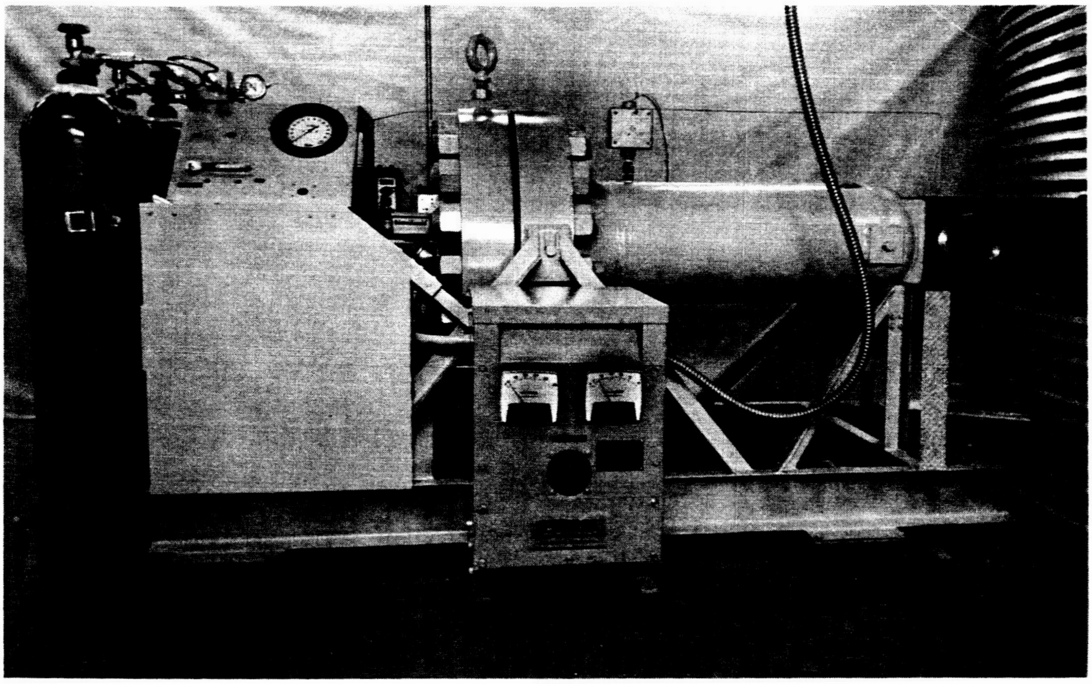


Figure 9. Litton ASD Wind Tunnel Facility

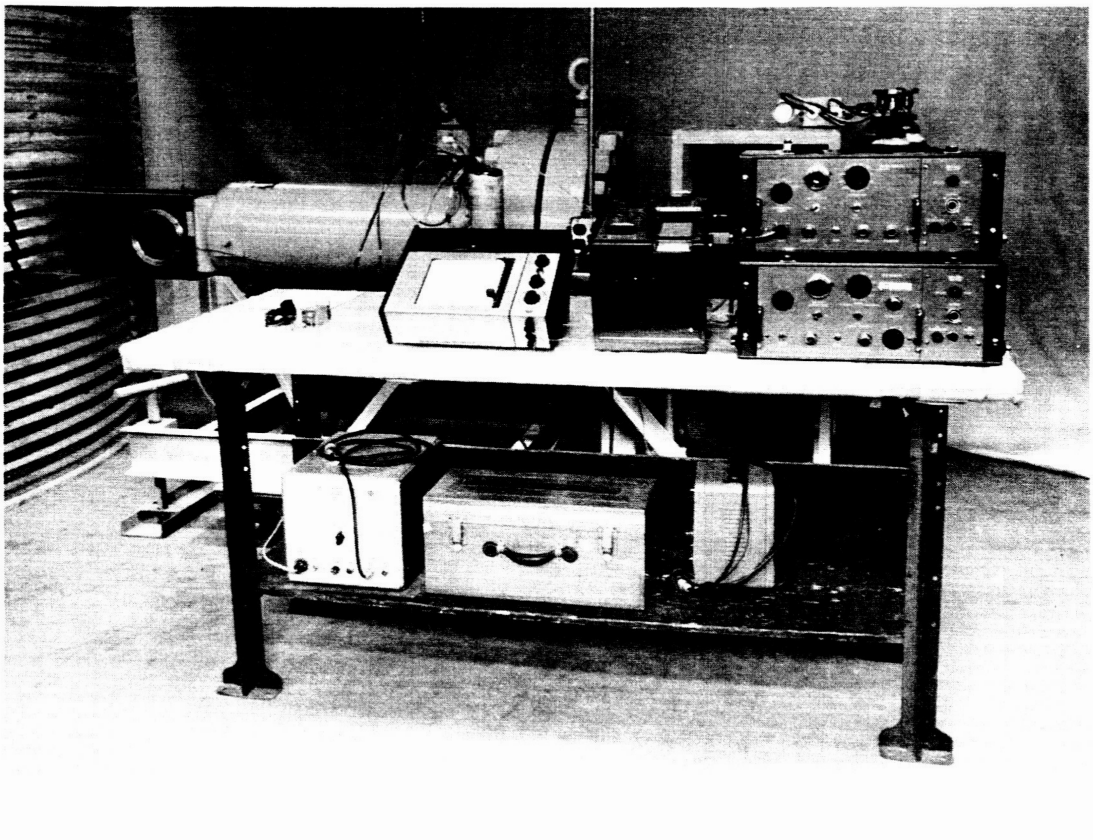


Figure 10. Wind Tunnel Instrumentation

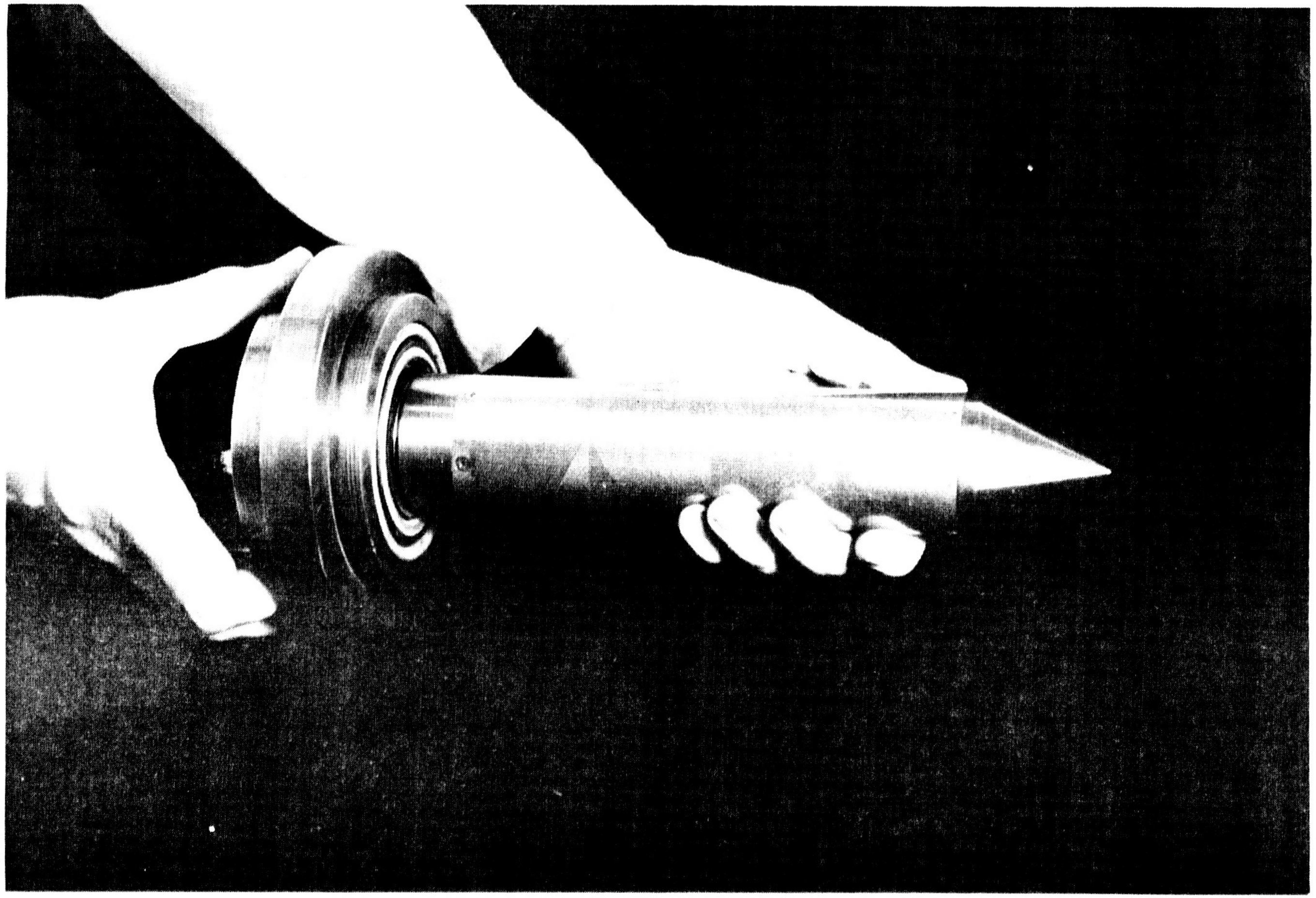


Figure 11. Filter Assembly

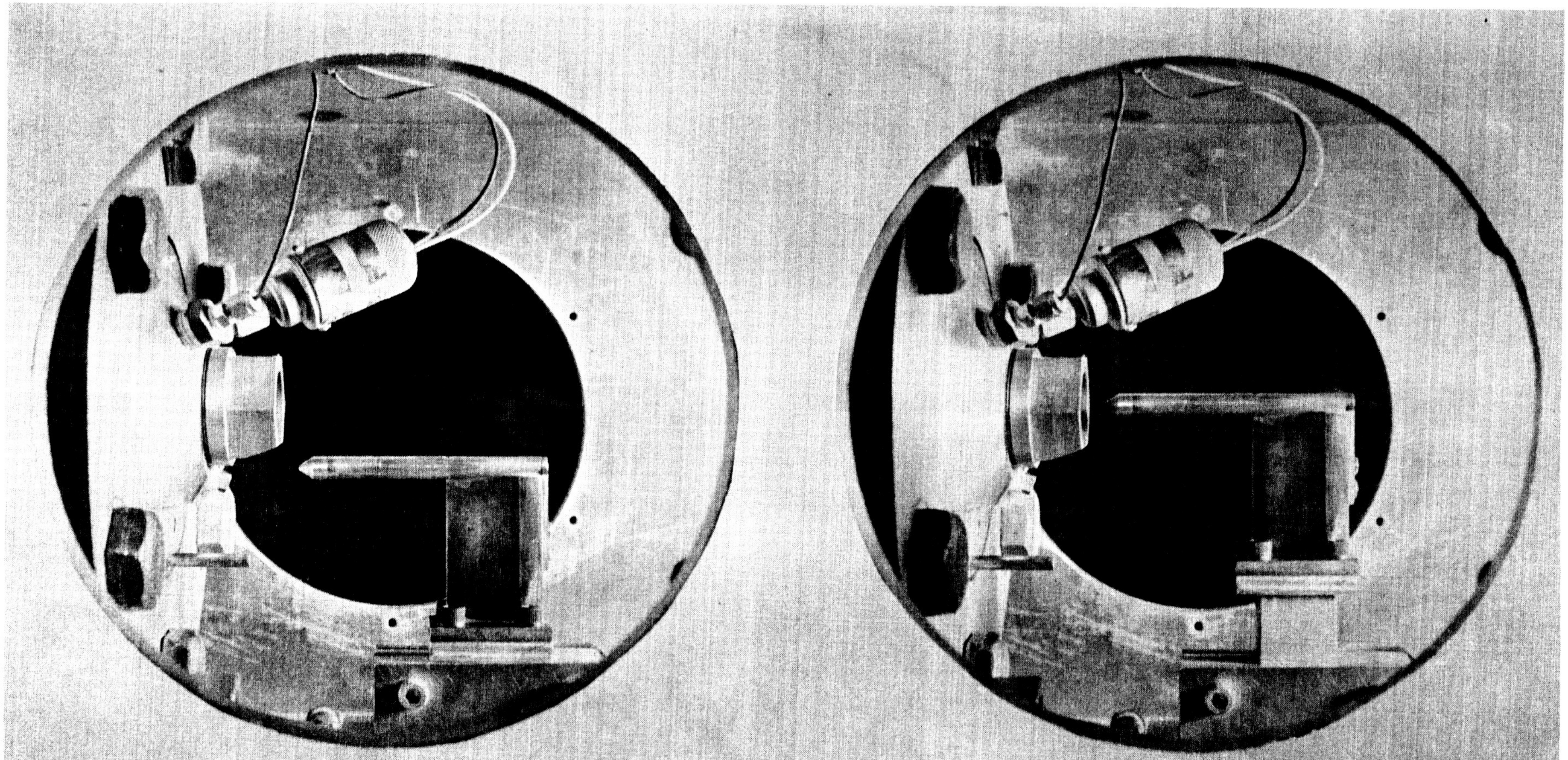
The heat-exchanger consists of a cylindrical pressure-vessel, with a 2-inch-thick insulation on the inside. Heat is stored in the system by using small aluminum-oxide pebbles (0.1-inch-diameter), forming a 7-inch-diameter bed 46 inches long. The wind tunnel running time varies from 5 to 15 seconds, depending on the stagnation-pressure utilized. If further probe calibrations should be performed, it would be advantageous to reduce the nozzle diameter to approximately 3/8 inch, increasing the running times considerably.

A mechanism for rapid insertion of the total-temperature probes into the airstream after the flow had been stabilized was designed and fabricated. This component is shown in Figure 12. This device is also utilized to withdraw the probe before the flow breaks down. In addition to protecting the probe from the stopping and starting loads, this technique allows a convenient measurements of probe-response time for each test condition. Our measurement accuracy was not compromised by the short running-times, because the probes have response-times of the order of 0.1 second.

B. Instrumentation

1. Temperature

Both the probe and the stilling-chamber stagnation-temperature were measured on a Brown self-balancing strip chart recorder which had been carefully calibrated. During the early runs, the temperature data were measured with a manually-balanced potentiometer, but it was found that better accuracy and repeatability could be obtained, if the more rapidly responding self-balancing recorder were utilized. A precision (thermocouple-grade) knife switch was utilized to connect the two different thermocouple outputs to the recorder.



a. Probe retracted   b. Probe inserted

Figure 12. Probe Insertion Mechanism

2. Pressure

The tunnel stagnation pressures were measured with a Heise pressure gauge. Downstream vacuum and the nozzle exit static pressure were measured on a conventional mercury manometer board.

C. Test Procedure

The following test procedure was utilized at both ASD and AHL. First the storage bed was heated to the appropriate temperature range, with the bed temperature monitored by several thermocouples at strategic locations. During some of the high stagnation pressure runs, the storage heaters both at ASD and at AHL were not able to provide a constant stagnation temperature. Thus, during each run there was a slight change in this value; so the procedure was to start at the high stagnation pressure values and reduce the pressure by small amounts to acquire a series of data points over the complete stagnation pressure range, at the same stagnation temperature. After the stagnation pressure had been stabilized at each value, the procedure was to record the tunnel stagnation temperature, switch to the temperature probe, and then switch back to the tunnel stagnation temperature reading. Thus, a stagnation temperature average, before and after the recording of the temperature probe readings, was obtained. For most of the runs, the temperature difference before and after the probe reading was of the order of one or two degrees Fahrenheit. Data then were taken, starting at the lowest stagnation pressure and increasing to the higher values.

D. Discussion of Probe Errors

The sources of errors which can influence the reading of a total temperature probe can be grouped into three categories:

1. Radiation Error

Whenever a difference in temperature exists between the sensing element and its surroundings a certain amount of heat can be transferred to or from the junction, depending upon the relative magnitudes of the temperatures. This error can be reduced by a control of the radiation interchange factor between the sensing element and the surroundings. A convenient way to accomplish this, is to provide one or more radiation shields around the sensing element. Desirable characteristics of such shields are small thermal masses and high reflectivities (i. e., low emissivities). These shields are also influenced by the same errors that affect the junction itself, but by control of the airflow over the various shields the radiation loss can be made almost negligible.

2. Conduction Error

If a temperature gradient exists between the sensing element and the lead wires a substantial amount of heat can be lost by conduction. This error can be reduced with small-diameter wires, which have less capacity to conduct heat away from the junction, and by the elimination of any large thermal masses which can draw heat away.

3. Compressibility Error

If the flow-velocity over the junction is large enough so that compressibility effects occur, the sensing element will reach a temperature which is smaller than the freestream total temperature. This effect can be considered as an "efficiency factor" in converting energy of directed motion to energy of random motion. If the radiation and conduction heat losses are reduced to zero, the sensing element will indicate a recovery-temperature which is a function of Mach number and the configuration of the sensing element.

An important parameter which controls the amount of heat or energy transferred to the sensing element is the ratio of vent hole area to entrance area. In probes designed for supersonic streams it is usually best that the probe lip shock is not swallowed but remains in front of the probe. The flow is then decelerated adiabatically, and added improvement can be made by further reducing the velocity through the addition of a constant area channel ahead of the sensing element.

For the small probes desired for the present application no attempts were made to provide multiple shielding or to try to study the effects of various entrance or vent hole areas. Rather, the major effort was the development of an extremely small probe which could withstand high temperatures and pressures and also have a reasonable recovery factor and response characteristics.

In summary, it can be stated that attainment of a probe which essentially reads the total temperature of the freestream requires that the heat transferred to the wire by forced convection be much larger than that taken away by radiation and conduction.

III. PROBE DESIGN AND FABRICATION

Referring to Figure 1, the small size of the probes is readily apparent. Special fabrication techniques had to be developed, and fine control of the assembly procedure was necessary to insure like performance of probes of the same configuration. The procedures utilized are much too detailed to be described here; therefore, only a brief description of each probe configuration will be presented.

The micro-welding operations were performed with a Unitek Weldomatic spot welder, with the probe components positioned and held by two Emerson micromanipulators. All assembly operations were observed with a Bausch and Lomb stereo zoom microscope.

Several probes were assembled from parts and drawings furnished by the George C. Marshall Space Flight Center. Photographs of these probes are shown in Figures 13, 14 and 15. The outer casing is made of 0.028-inch O.D. hypodermic tubing. The sensing element is a commercially available micro-miniature thermocouple assembly, having a sheath diameter of 0.015 inch. The bead thermocouple sensing element is made of 0.0005-inch-diameter chromel-alumel wire. Two slots cut into the tip of the outer sheath serve as vent-holes for self aspiration.

Two other probes of the same configuration were fabricated having a copper constantan bead junction assembly. The basic features of this probe are shown in Figure 1.

The smallest temperature probe configuration utilized was housed in 0.013-inch O.D. hypodermic tubing. The lap junction was made of chromel-alumel wire, and the leads were inserted into a 0.0028-inch-diameter quartz tube to prevent short circuits (see Figures 16 and 17). Several junction configurations were utilized for this probe. In addition to a 1/2-mil junction, several probes were made utilizing 1-mil

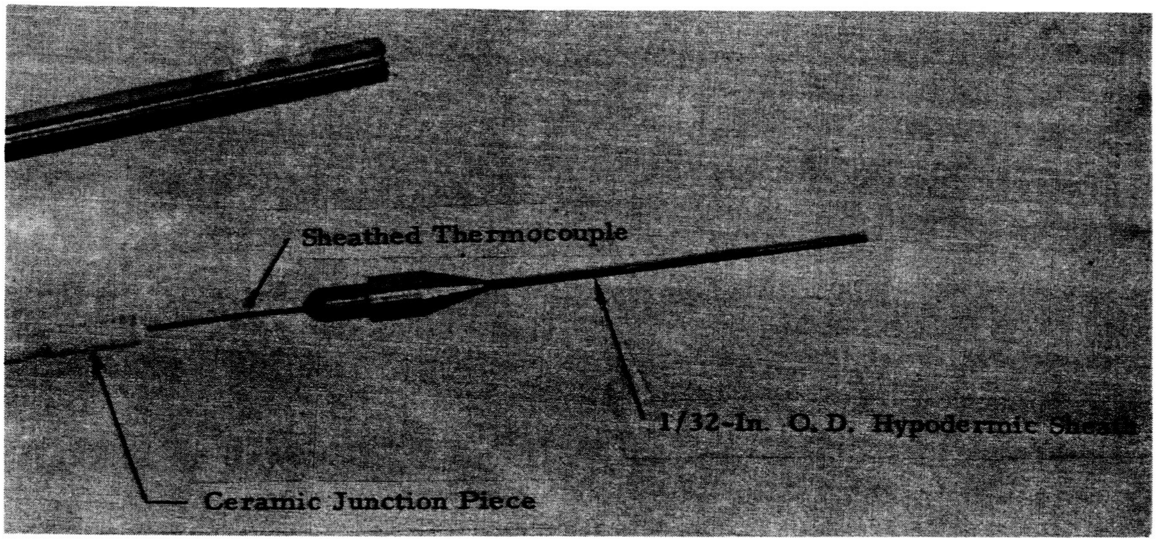


Figure 13. Partially Assembled Probe (large configuration)

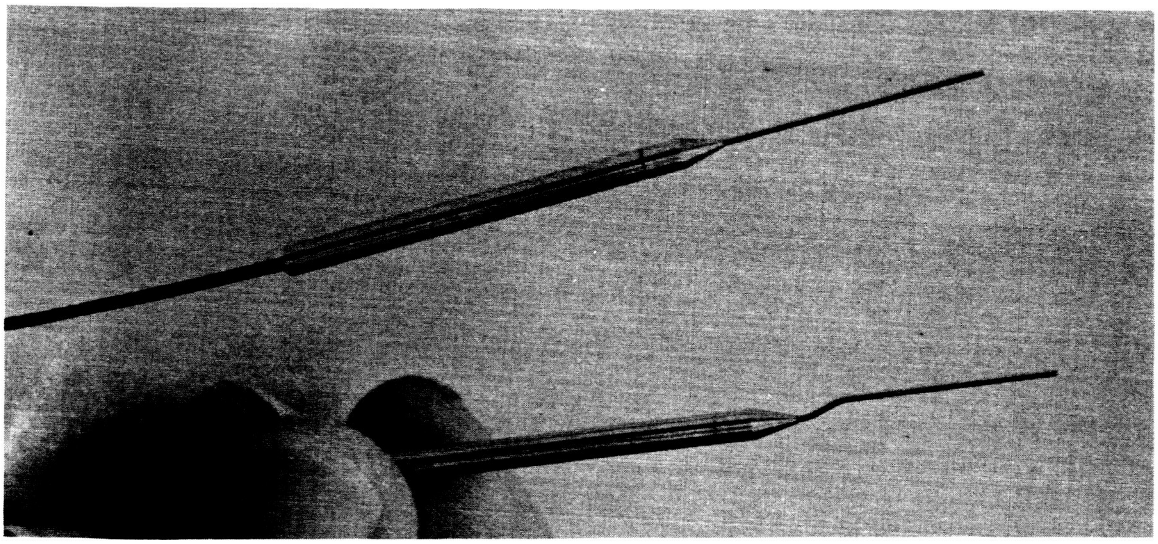


Figure 14. Completed Probes

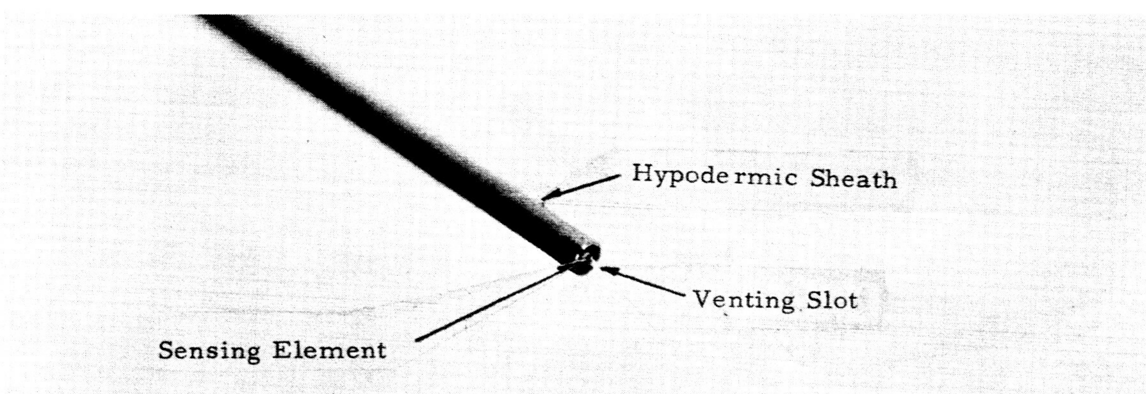


Figure 15. Micro-photograph Showing Thermocouple Junction

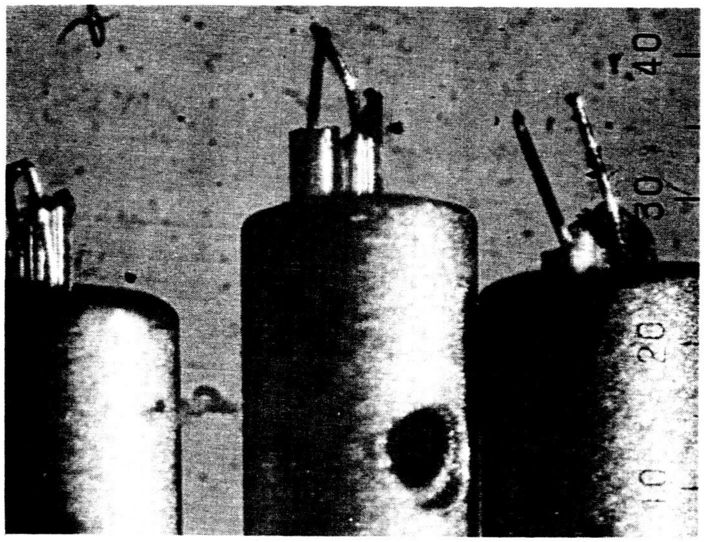


Figure 16. Micro-photograph Showing Thermocouple Junction Details (small configuration)

Figure 17. Micro-photograph of Completed Probe

(70X)

thermocouple wire, and a third type was made with commercial 1-mil-diameter beaded thermocouple junctions, supplied by Omego Engineering Corporation. A drawing of this probe configuration is shown in Figure 1.

Another probe configuration that was not as small, but was easier to fabricate, was housed in 0.018-inch-diameter stainless-steel hypodermic tubing. The inner thermocouple assembly was made of commercially available Xactpak shielded chromel-alumel thermocouple wire obtained from the Gordon Co. It has an outer 0.010-inch O.D. inconel sheath, and the thermocouple wires are 0.0015-inch-diameter, separated by magnesium oxide insulating material. The junction location with respect to the probe leading edge and venting holes, is similar to the earlier configurations, as shown in Figure 1.

IV. DISCUSSION OF RESULTS

Several total temperature probe configurations were calibrated, in the AHL calibration tunnel, and in the ASD facility. All of the probes are grouped into three major configurations, referred to as "small", "medium", and "large". The data are presented in the form of a probe recovery factor σ. This is a convenient representation which separates data for the various Mach numbers and allows multiple presentation of results in a single plot. The definition utilized is

$$\sigma = \frac{T_o' - T_\infty}{T_o - T_\infty}$$

where T_o' is the probe recovery temperature, T_o is the wind-tunnel total temperature, and T_∞ is the freestream static temperature (a function of the total temperature and freestream Mach number). The data are plotted as a function of unit Reynolds number Re' which is evaluated at conditions behind the normal shock wave ahead of the probe.

Shown in Figure 18 are calibration data for the large probe configuration which was fabricated according to a George C. Marshall Space Flight Center design. The initial plan was to calibrate all probes at supersonic Mach numbers of 1, 3 and 5 over a stagnation-pressure range of 0 to 500 psig, while varying the freestream total-temperature to a maximum value of 1100°F. However, sandblasting problems were encountered in both wind tunnel facilities, so in most cases it was not possible to obtain a complete calibration before a probe was damaged. However, this problem was solved during the later phases of the program, when the smaller improved probe configurations were tested and data over the complete range were obtained.

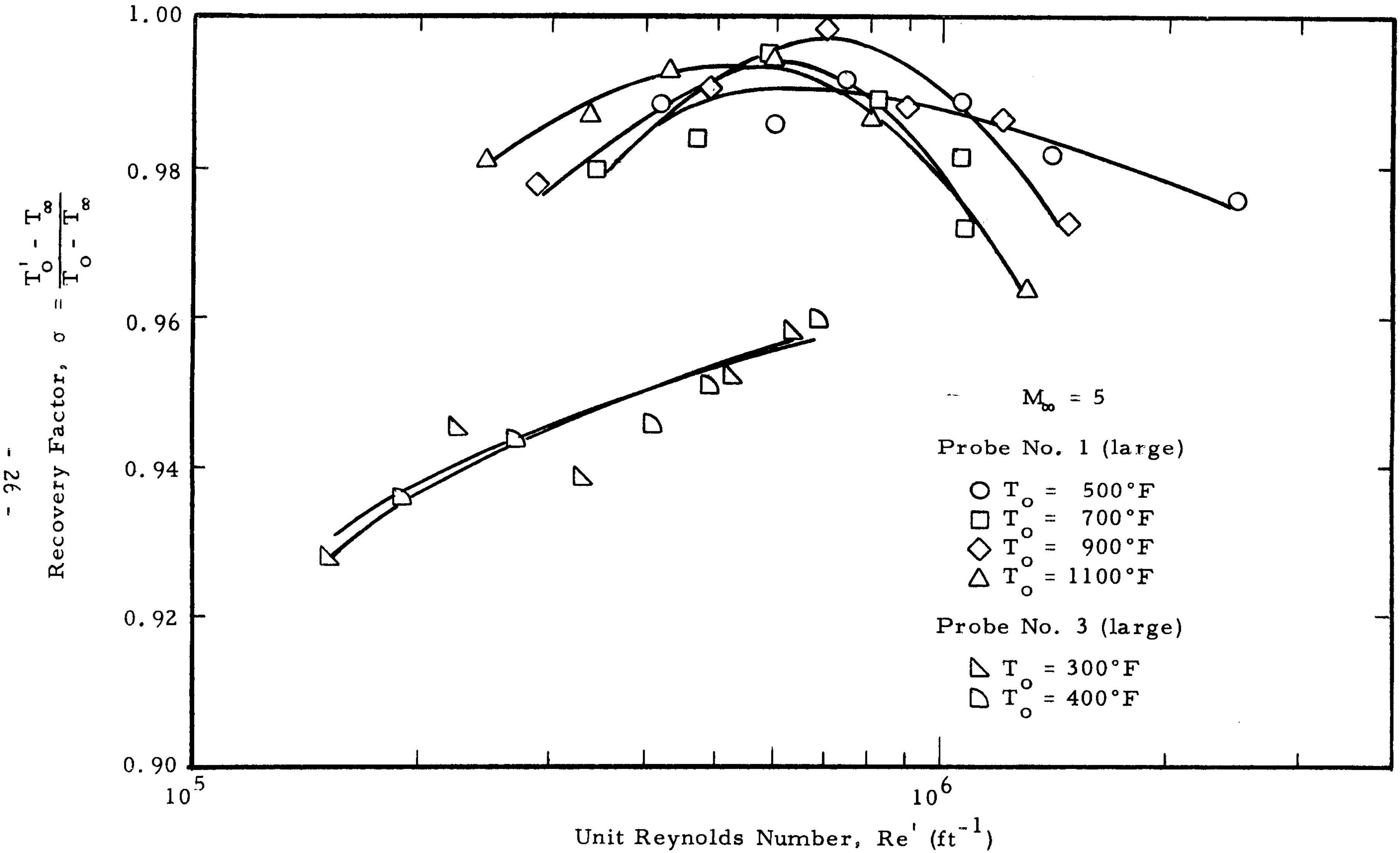


Figure 18. Calibration of Large Total Temperature Probes (No. 1 and No. 3)

Presented in the figure are calibration data for probes 1 and 3. Probe 1 was calibrated at Mach 5 and stagnation temperatures varying from 500°F to 1100°F, while probe 3 was tested only at Mach 3, and stagnation temperatures of 300°F and 400°F. As shown in the figure, slight changes in performance, because of the variation of total temperature, are noted, although no repeatable or systematic trends are evident. The apparently large separation between the two sets of data is caused by the non-dimensional representation of probe recovery-factor, which is a function of the freestream Mach number.

An unexpected and unexplained drop in the probe recovery-factor at the higher Reynolds numbers was first detected when utilizing this probe. Sufficient time was not available to make a detailed study of the effects of variation of the size of the aspirating passages or junction placement with respect to the probe opening, so it is possible that this behavior is representative of the small types of probes being utilized. Because of the small probe sizes it is also quite possible that slip flow conditions are being approached. It is especially true of the smallest probe configuration tested. We feel that this behavior should be studied further before any definite conclusions are drawn.

Data for two of the small probe configurations are presented in Figure 19. The upper portion of the figure shows data for probes 9 and 10 at a freestream Mach number of 5 and a stagnation temperature of 600°F. Extreme care was taken during the fabrication of these probes, to make them as nearly alike as possible, to minimize the effects of variations in configuration. These data indicate that it is possible to utilize a very small probe design and obtain similar performance for different probes. The lower portion of the figure presents data for probe 9, at a freestream Mach number of 3 and stagnation temperatures of 300°F and 400°F. A discernible effect of temperature is noted.

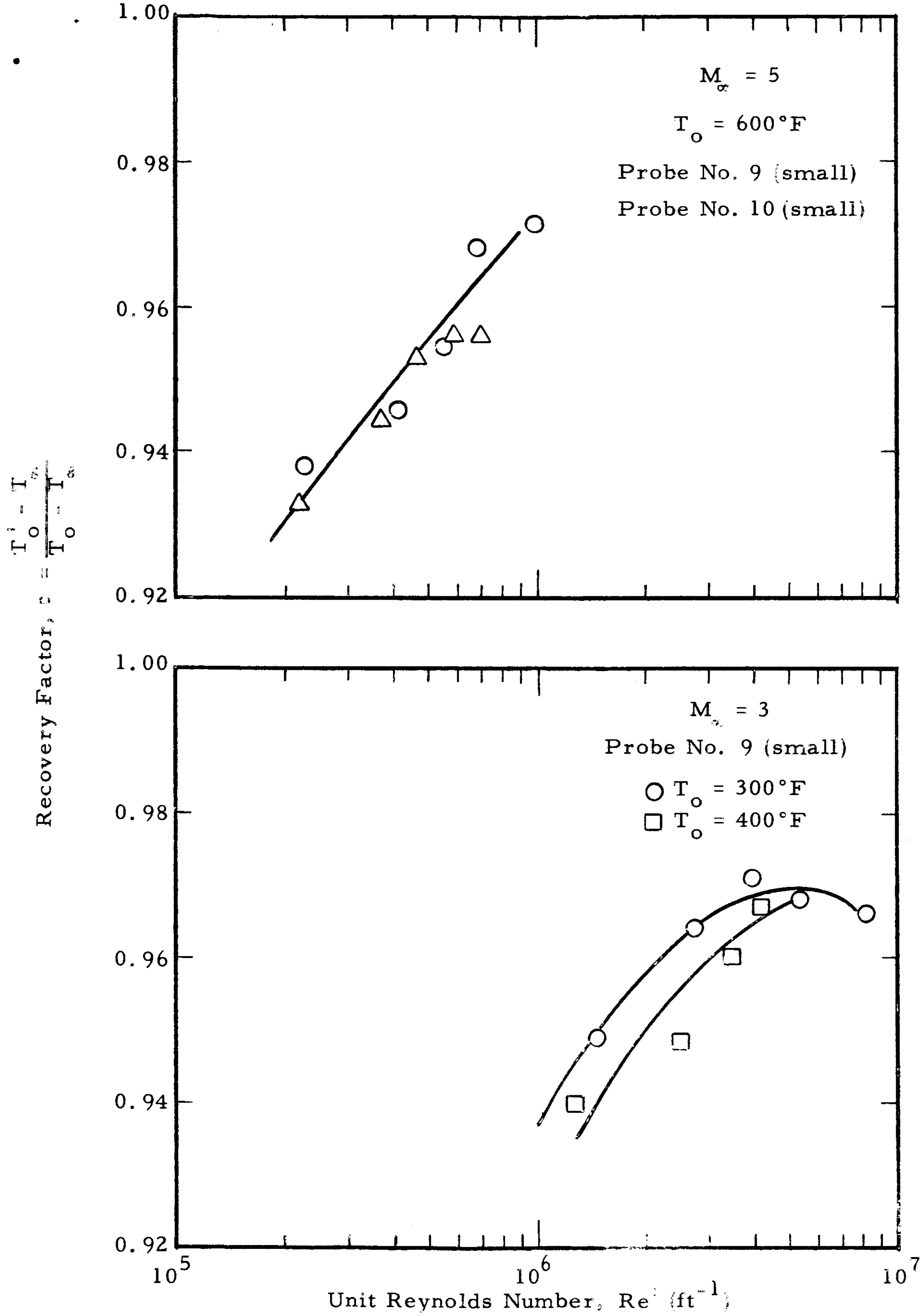


Figure 19. Calibration of Small Total Temperature Probes (No. 9 and No. 10)

A more complete calibration for the small probe configuration is presented in Figure 20. These data were obtained at Mach 1, 3, and 5 over a stagnation temperature range of 500°F to 1100°F. Only small changes in probe performance were noted for the different junction configurations. When the sandblasting problems were first encountered it was through that an increase in the junction size from 1/2 mil to 1 mil would reduce the probe mortality rate. However, after the airflow in both tunnels was cleaned no changes in probe failure rates were noted. A slight downward trend in the recovery factor at the higher Reynolds numbers is again noted at all Mach numbers. The slight upward trend at the lower Reynolds number is caused by operation near flow-breakdown conditions.

Calibration data for the medium probe configuration are shown in Figure 21. These data show a pronounced drop in the recovery factor at the higher Reynolds numbers. Additional data for this same probe configuration are shown in Figure 22, for probe 17.

Data obtained in the ASD calibration facility are essentially in agreement with the AHL data, although slightly higher recovery factors were obtained. This tunnel does not have provision for operating at lower pressures, where most of the interesting effects take place, because of lack of a vacuum capability. This tunnel was mainly utilized to isolate any possible effects of the wind tunnel walls in the AHL enclosed test section. In addition, because of its higher pressure capability, the mechanical performance of the probe was studied. With the improved filter design it was shown that all of the probe configurations tested in the ASD facility would perform satisfactorily at stagnation pressures to 500 psig and stagnation temperatures to 1100°F. Over this stagnation pressure range a recovery factor of about 0.98 was obtained for all probes.

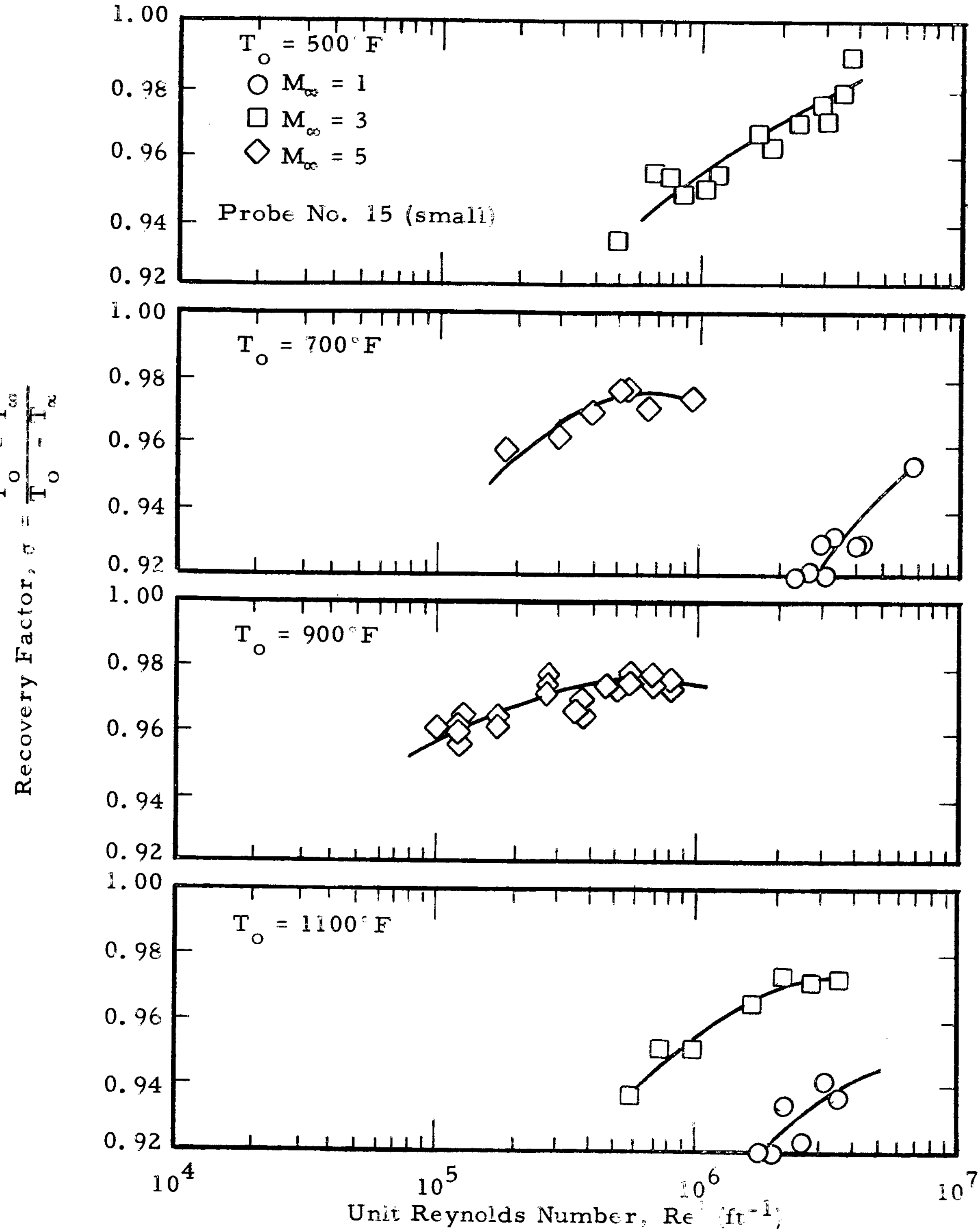


Figure 20. Calibration of Small Total Temperature Probe (No. 15)

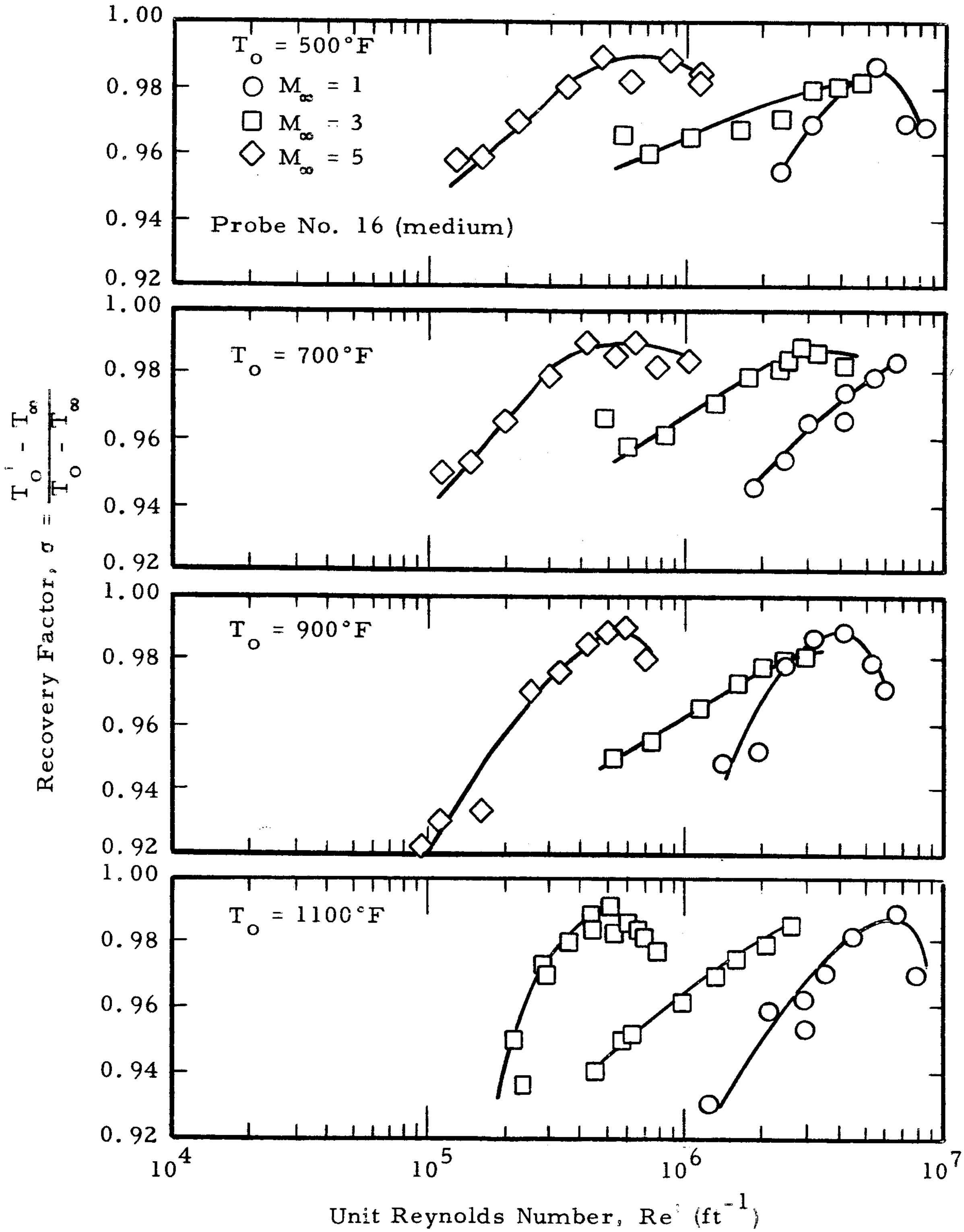


Figure 21. Calibration of Medium Total Temperature Probe (No. 16)

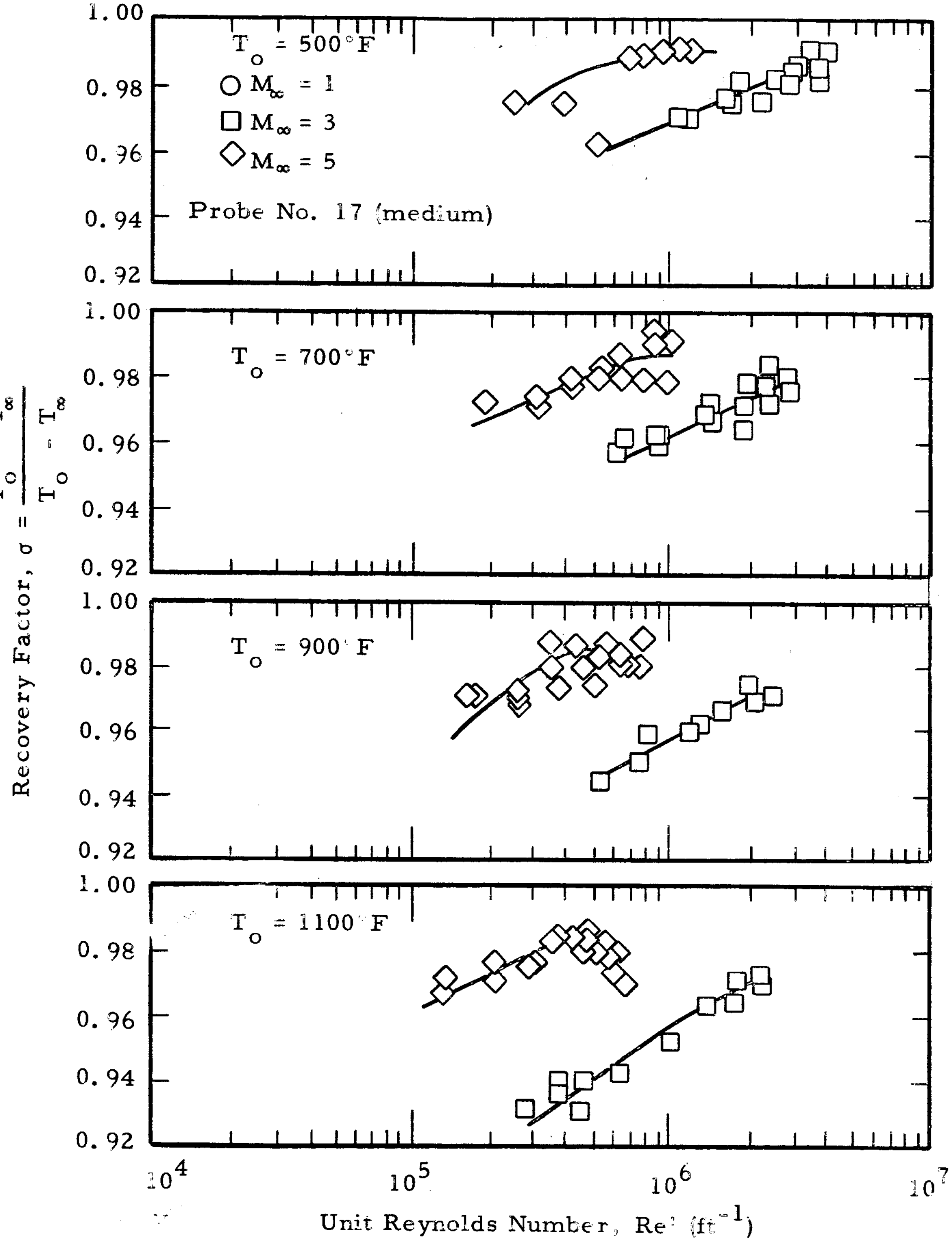


Figure 22. Calibration of Medium Total Temperature Probe (No. 17)

V. SUMMARY AND CONCLUSIONS

A nine-month program to design, fabricate, and calibrate subminiature total temperature probes has recently been completed for the George C. Marshall Space Flight Center. For these probes small size was considered more important than a very high recovery factor, and a large amount of the effort was directed toward the development of fabrication techniques for these extremely small probes. All of the probes tested had a single radiation shield of stainless steel, and no attempts were made to provide multiple shielding. During this program the following tasks were accomplished:

1) A study was made of the literature pertaining to total temperature probes in general. No mention could be found of any probes approaching the size required.

2) Various fabrication techniques and assembly procedures were developed and utilized, to allow manufacture of the basic probe configuration. Probes having diameters from 0.013 to 0.028 inch were fabricated. All probes were self aspirated, and several different junction configurations were utilized. Thermocouple wire diameters ranged from 0.0015 to 0.0005 inch.

3) Representative models of these probe shapes were calibrated in the free-jet wind tunnel facility at the Applied Science Division and the enclosed-jet facility at the University of Minnesota Aero-Hypersonic Laboratory. The stagnation temperature was varied from 100°F to 1100°F, and stagnation pressures varied from ambient to 500 psig. The probes were tested at subsonic velocities and at Mach 1, 3 and 5.

4) Preliminary response time measurements were performed which indicate that the probes have time constants of the order of 0.1 second.

VI. SUGGESTIONS FOR FUTURE STUDIES

On the basis of the tests carried out under this contract, the following recommendations for future probe fabrication and calibration studies are presented:

1) Improved radiation shielding should be devised to reduce the radiation error. This can be accomplished with a radiation shield made of metal having high reflectivity, such as gold or platinum. We believe that it is possible to make a double-shielded probe having an outside diameter of less than 1/32 inch.

2) Improved thermocouple junction configurations should be studied to reduce conduction errors. This would include variations in shape, placement of the junction with respect to the probe body, ventilating openings, and probe inlet.

3) Studies of the effects of variation of vent-area to inlet-area ratio should be carried out.

4) As the major goal of this program was to develop an extremely small probe, with small size being more important than the attainment of high recovery factors, the precision in measurements that would normally be exercised in a probe calibration study were not considered appropriate. We suggest that further studies should be made using slightly smaller nozzle exit diameters. This will allow a more careful control of the total temperature and freestream Reynolds numbers, keeping them at constant values. The utilization of more accurate temperature read-out devices, such as manual balancing potentiometers, would then be feasible.

5) Further study of the factors causing the drop in the calibration curve should also be carried out. If this behavior were caused by slip flow effects, one would expect that the smallest probe sizes would show a more pronounced dip. However, this was not proven to be the case, since the large probe configuration had a more pronounced drop at the higher Reynolds numbers. Other possibilities should be considered.

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